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TARDEC No. TR13669

RESEARCH NEEDED FOR MORE COMPACT INTERMITTENT COMBUSTION PROPULSION SYSTEMS FOR ARMY COMBAT VEHICLES

VOLUME I
Executive Summary and Main Body

INTERIM REPORT
TFLRF No. 296

By
Blue Ribbon Committee (BRC)

Prepared for
U.S. Army Tank-automotive and Armaments Command (TACOM)
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Because of the unique performance requirements of combat vehicles, it is not possible to achieve the required propulsion system power density by adaptation of commercial engines; the **Army** must ensure that the research and development required to achieve the needed propulsion system power density is accomplished.

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To assist TACOM in identifying the research and development needed in the next decade for intermittent combustion combat engines, a BRC was established. Assuming the BRC recommended research is successfully accomplished, propulsion system volume could be reduced for the same power output, or for the same system volume, vehicle power could be markedly increased. The BRC identified hp/ton as a significant vehicle performance factor. By inserting advanced propulsion systems AIPS, or BRC, in the **existing system** volume of five different vehicles, the BRC study shows that hp/ton increases are dramatic. For example, if development of the AIPS were completed, hp/ton for the AGT1500 hp M1 would increase from 22.2 hp/ton to 35 hp/ton using AIPS technology; use of BRC technology would result in 43.3 hp/ton. **For new vehicles**, again assuming completion of AIPS development, a weight decrease of 7 tons from a nominal 60-ton AGT1500 vehicle could be achieved; an additional 3 tons could be achieved using BRC technology.

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Note: Appendices in both Volume I (Arabic numerals) and Volume II (Roman numerals) correspond with like numbered sections in the Volume I narrative, to facilitate the location of common report information and maintain continuity. Hence, certain unnecessary numbers in the appendices have not been used. Volume II expands selected sections of Volume I.

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GLOSSARY — VOLUME I

AIPS	Advanced Integrated Propulsion System
AVCR	Air-Cooled Variable Compression Ratio (piston)
BFD	Battlefield Day (duty cycle)
bhp	brake horsepower
BMEP	Brake Mean Effective Pressure
BRC	Blue Ribbon Committee
BSAC	Brake Specific Air Consumption
Btu	British thermal unit
CATTB	Component Advanced Technology Test Bed
CCATTD	Common Chassis Advanced Technology Transition Demonstrator
CCD	Caterpillar Compact Diesel
cfm	cubic feet per minute
dAIPS	diesel Advanced Integrated Propulsion System
EM	Electromagnetic (gun)
ETC	Electrothermal Cannon
F/A	Fuel Air Ratio
F&L	Fuels and Lubricants
ghp	gross horsepower
GVW	Gross Vehicle Weight
hp	horsepower
HPD	Higher Power Density
HPDPS	Higher Power Density Propulsion System
kph	kilometers per hour
LCTE	Lowest Comparable Technology Estimate
LER	Loss Exchange Ratio
LHV	Lower Heating Value
MTC-B	Mobility Technology Center-Belvoir
NA	Naturally Aspirated
N/A	Not Available
NBC	Nuclear, Biological, and Chemical
NEA	Northeast Asia
PA	Peacetime Annual (duty cycle)
Pmfld	Manifold Pressure
RFP	Request for Proposal
RPI	Rotary Power International
rpm	revolutions per minute
SWA	Southwest Asia
SwRI	Southwest Research Institute
TACOM	U.S. Army Tank-automotive and Armaments Command
tAIPS	turbine Advanced Integrated Propulsion System
TARDEC	U.S. Army Tank-Automotive Research, Development and Engineering Center
TE	Tractive Effort

GLOSSARY — VOLUME I, CONT'D

TFLRF	TARDEC Fuels and Lubricants Research Facility (SwRI)
TMEPS	Transverse Mounted Engine Propulsion System
TRADOC	U.S. Army Training and Doctrine Command
TRR	Top Ring Reversal

VOLUME I

Executive Summary and Main Body

1. EXECUTIVE SUMMARY

Future air-land battle operation concepts dictate that combat vehicles have increased lethality, mobility, survivability, and deployability. In addition, future vehicle use may need substantially greater (up to 40 percent) power requirements over mobility needs, i.e., electric armor, active suspension, environmental control, battlefield management, survivability, perhaps weaponry, etc.

Increasing propulsion system power density will contribute to achieving the above objectives. For **new** vehicles, it increases design flexibility, resulting in reduced vehicle length, height, and weight, which increase survivability, deployability, sustainment, and maneuverability. For **existing** vehicles, it permits substantial up-powering.

Because of the unique performance requirements of combat vehicles, it is not possible to achieve the required propulsion system power density by adaptation of commercial engines; the **Army** must ensure that the research and development required to achieve the needed propulsion system power density is accomplished.

To assist the U.S. Army Tank-automotive and Armaments Command (TACOM) in identifying the research and development needed in the next decade for intermittent combustion combat engines, a Blue Ribbon Committee (BRC) was established. This reports their deliberations and recommendations. Assuming their recommended research is successfully accomplished, Fig. 1-1 indicates that for the same power output, system volume can be markedly reduced, or for the same system volume, vehicle power can be markedly increased.

The BRC identified hp/ton as a significant vehicle performance factor. Assuming completed development of the Advanced Integrated Propulsion System (AIPS) and successful completion of the BRC recommended research, Fig. 1-2 illustrates the increases in hp/ton that could be achieved by inserting advanced propulsion systems in the **existing system volume** of five different vehicles. The increases are dramatic; they reflect the reduced volume requirements of high power density propulsion systems (HPDPS).

New vehicles have design flexibility not available for existing vehicles. Consequently, the gains for new vehicles are not as dramatic as for existing vehicles. However, assuming completed development of AIPS and successful completion of the BRC recommended research and keeping the same hp/ton, it is estimated that use of AIPS technology would reduce a nominal 60-ton vehicle using AGT1500 technology to 53 tons; use of BRC technology would provide a reduction to 50 tons. These weight decreases would be helpful in meeting Army objectives to lighten the force. Use of the same technology development for both **existing** and **new** vehicles would minimize total development costs and extend lifetime and usefulness of the existing fleet.

To ensure future availability of HPDPS, the BRC recommends that TACOM conduct research that will 1) increase the fraction of cylinder air used for combustion as well as the mass flow rate of combustion air; 2) accelerate propulsion system simulation efforts to aid system optimization; and 3) maintain an awareness of continuing new developments through selected, very long-range research.

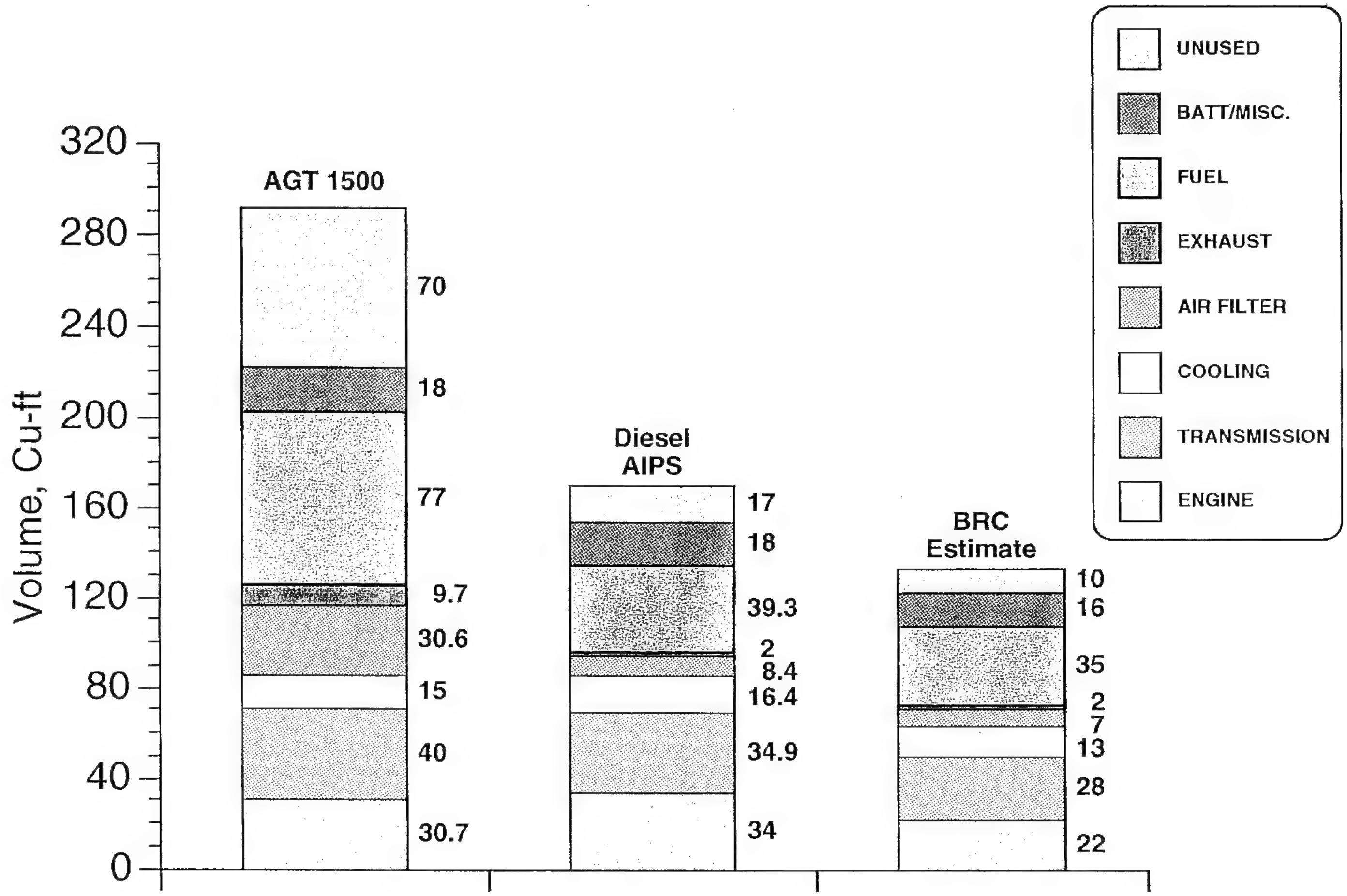


Figure 1-1. Volume reductions achievable by using high power density propulsion systems

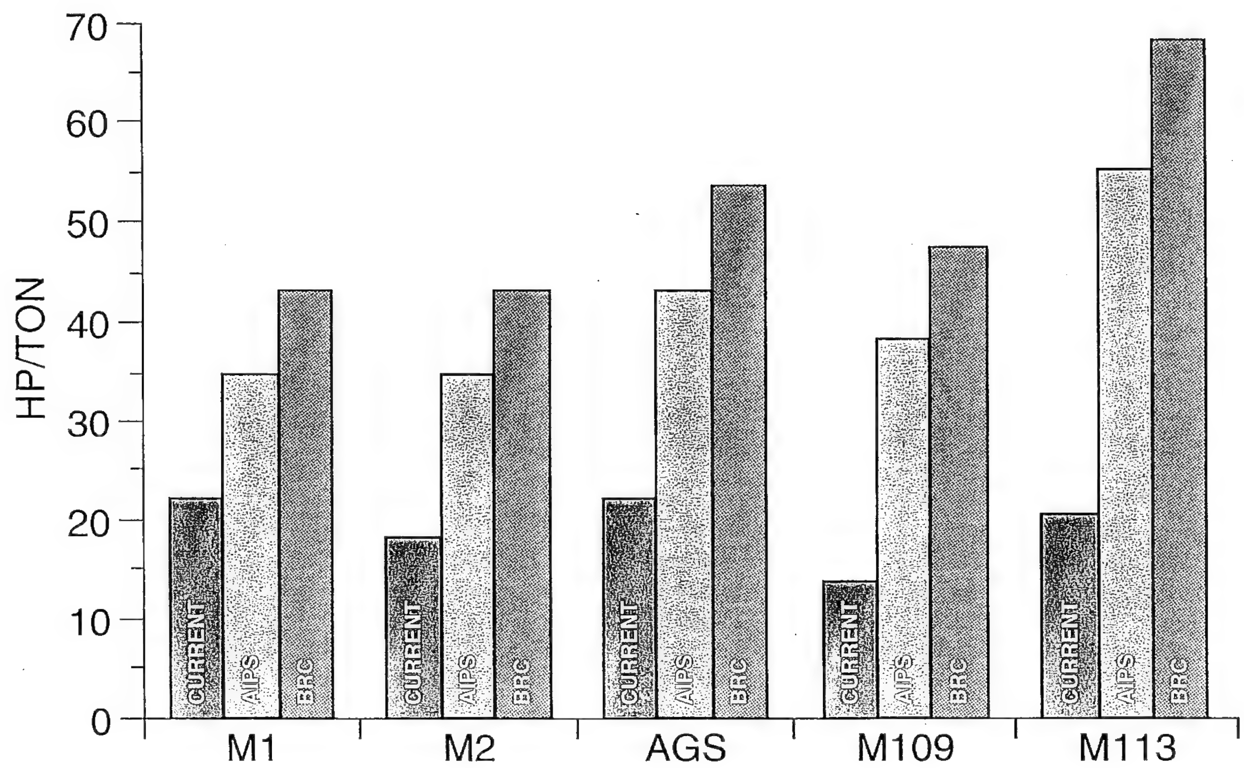


Figure 1-2. Increases in hp/ton achievable by using high power density propulsion systems in existing vehicles

2. BACKGROUND AND REASONS FOR THE STUDY

The U.S. Army has a continuing need to develop more compact and lightweight powerplants to meet the requirements of future combat vehicles. Future combat vehicles require dramatic reductions in size and weight to improve survivability and to provide for rapid deployment to any location in the world. Improved mobility is also needed to enhance effectiveness on the battlefield. Also, improvements in reliability, durability, and maintainability are required to reduce life-cycle costs and to reduce the logistical burden.

These stringent future vehicle requirements place some very severe demands on the propulsion system. The propulsion system is obviously a major vehicle component that must be improved if the combat vehicles of tomorrow are to meet their performance, operational, and life-cycle goals.

The Propulsion Systems Division at the U.S. Army Tank-automotive and Armaments Command (TACOM), Warren, MI, is responsible for the research and development of propulsion systems for Army Ground Vehicles. In 1982, TACOM initiated the development of two future-generation propulsion systems for combat vehicles, namely the Advanced Integrated Propulsion System (AIPS). The two approaches developed were 1) a diesel engine-powered AIPS (dAIPS) and 2) a gas turbine-powered AIPS (tAIPS). The prime contractors were Cummins Engine Company, Inc. for the dAIPS and General Electric Company for the tAIPS.

After completion of exploratory development and demonstration of both AIPSs under TACOM contracts in 1991, certain AIPS technology and hardware were selected by the two prime contractors for further development under the Common Chassis Advanced Technology Transition Demonstrator contracts.

At this time, TACOM is at a pivotal point in determining the direction of its Intermittent Combustion Engine Propulsion Systems Research and Development Program for Future Combat Vehicles in the post-2000 time frame.

It is judged that the Intermittent Combustion Engine will continue to be a strong contender to power future combat vehicles. Since the research and development of propulsion systems involve large investments in manpower and funds, it is imperative that such research be directed toward the most fruitful areas for technology advancements. If a more compact and lighter weight propulsion system is to be achieved, it is essential to identify now the limiting technical barriers and the research needed to eliminate these barriers.

As a means of more completely identifying these barriers and the research needed to overcome them, TACOM established a Blue Ribbon Committee (BRC) consisting of eminently qualified experts in engine/propulsion system technologies. The primary reason for organizing a BRC was to provide a recommendation from an independent source regarding the direction of research in Intermittent Combustion Engine technology that TACOM should pursue to best meet future combat vehicle propulsion system requirements. BRC membership consists of the following:

- Professor Phillip S. Myers, Chairman
- Dr. Simon K. Chen
- Mr. Edward H. Dewes
- Dr. Donald M. Dix
- Mr. Nigel F. Gale
- Mr. Sidney J. Lestz
- Dr. Patrick J. McCleer

This BRC study effort was coordinated with other Army agencies, including the U.S. Army Training and Doctrine Command (TRADOC); the Army Research Laboratory Propulsion Directorate at NASA Lewis Research Center, Cleveland, OH; and the U.S. Army Tank-Automotive Research, Development and Engineering Center (TARDEC), Mobility Technology Center-Belvoir (MTC-B), Ft. Belvoir, VA. Further information on members of the BRC can be found in Appendix II, Volume II. The BRC generously received and appreciated counsel and advice from numerous organizations that are listed in Appendix 2 of this volume.

3. PAYOFFS FROM HIGHER POWER DENSITY PROPULSION SYSTEMS (HPDPS) FOR FUTURE COMBAT VEHICLES

3.1 Introduction

3.1.1 The origins of future vehicles

For the foreseeable future, purchase of a few new vehicles (plus extension of the useful life of existing combat vehicles) is the most cost effective answer to meeting the Army's defense needs and budget constraints. However, to maintain international leadership, both new and retrofitted vehicles must have markedly increased vehicle performance plus auxiliary power capabilities, i.e., hp/ton must be dramatically increased. For existing vehicles, the propulsion system volume is predetermined. Thus, especially for existing vehicles, performance increases can only be achieved if volume propulsion system power density (i.e., hp/cu. ft) can be increased.

3.1.2 The gains from increased power density

Increased power density, estimated to be achievable as detailed in Sections 3.5.2 and 3.5.3 of this report, would permit the following:

1. Increases, ranging from 46 to 163 percent, in cross-country speed of existing vehicles;

2. Use of an electromagnetic (EM) gun or electrothermal cannon (ETC);

3. Use of active defense;

4. Significant increases in survivability due to a smaller silhouette, increased agility, hit avoidance, and rapidity of movement to new position with decreased exposure time;

5. Needed flexibility in the design of new vehicles to further increase survivability and ease of deployment; and

6. The addition of more fuel and/or ammunition to existing vehicles, thereby increasing range and/or survivability.

3.2 The Changing Combat Scene

In the last several years, there have been dramatic changes in the world power structure. These changes have increased the probability of smaller conflicts as opposed to a more global conflict. Smaller, more numerous conflicts will require more frequent and rapid deployment of combat vehicles, and the equipment and its required support must be readily transportable. Furthermore, changing combat tactics emphasize high cross-country speeds.

In response to this changing combat scene, TARDEC has adopted a number of Strategic Quality Goals and Objectives. The objectives pertinent to this report are given below.

Objective 6d. *Demonstrate Leap-Ahead Tank-Automotive Technologies.* "By the year 2000, demonstrate double speed and increased survivability, halve the weight, and digitize intra- and intervehicle command and control technologies."

Objective 6e. *Transition Technology to New Developmental Programs and Insert Into Existing Military and Commercial Systems.* "...productivity will be based on technological improvements which end up in new developmental programs or are inserted into existing vehicles."

3.3 The Implications of the Changing Combat Scene for Future Propulsion Systems

The TARDEC objectives previously described implicate three broad aims for future propulsion systems:

- To significantly increase propulsion system power from both a vehicle performance and a weaponry standpoint;

- To increase the performance and survivability, and thus the combat capabilities, of the existing fleet of combat vehicles; and

- To enhance the part that more compact propulsion systems can play in providing maximum flexibility in new combat vehicle design to increase survivability.

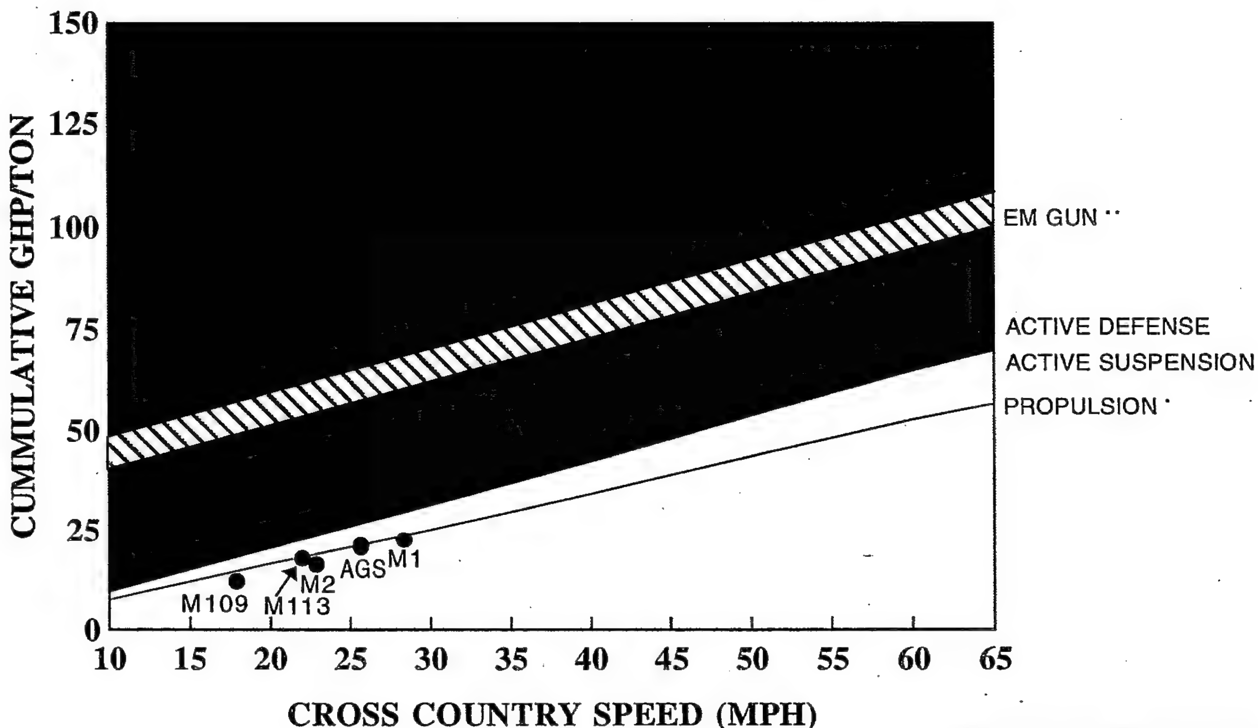
3.4 The Need for Dramatic Increases in Propulsion System Power

The implication for increases in propulsion system power is illustrated in Fig. 3-1, which presents data on cumulative gross horsepower/ton for the indicated uses versus cross-country speed. The curves below the blue area (propulsion, environmental control, and active suspension) represent power that must be supplied for the vehicle to operate at any given speed. The blue area represents a region of supplemental power (i.e., power not directly required for propulsion but needed, either constantly or intermittently, for auxiliary purposes). Examples would be active defense and the EM gun.

Propulsion and active suspension are the only items that require power increases with an increase in vehicle speed. Figure 3-1 shows that as speed decreases, for a fixed hp/ton, the power available for auxiliary use (blue area) increases. For example, the M1 has approximately 22 hp/ton. At maximum cross-country speed of approximately 28 mph, there is zero power available for auxiliary purposes, but at zero speed, 22 hp/ton is available for auxiliary power purposes.

Data points for five existing vehicles are shown in Fig. 3-1. Even at zero speed, none of these existing vehicles have sufficient power to permit use of an electromagnetic gun. In contrast, the hp/ton required to double vehicle speed would permit use of the EM gun at low cross-country speeds. Significant increases in hp/ton, and therefore in propulsion system power density, are needed to improve both vehicle performance and weaponry.

HP/TON VS. CROSS COUNTRY SPEED



* PROPULSION INCLUDES FIRE & ENVIRONMENTAL CONTROL

** EM GUN - TIME AVERAGED POWER FOR 5 SHOTS PER MINUTE

Figure 3-1. <u>hp/ton vs. cross-country speed (current technology)</u>

3.5 The Benefits of Achievable Increases in hp/ton

3.5.1 Background

Additional power for any vehicle, new or existing, can generally be employed for three purposes: survivability, lethality, and mobility.

Survivability uses power for nuclear, biological, and chemical (NBC) protection, stealth mechanisms, active armor, countermeasures, and threat sensing devices. The NBC and threat sensing are smaller, constant loads that are well established in usage. Stealth works only at very low speed and hence, while a moderate power consumer, does not compete with the mobility requirements which strain power capacity only at high speeds. Countermeasures and active armor are intermittent spike loads, usually electrical, that require the storage of moderate amounts of energy but are discharged with considerable power. Capacitance or kinetic energy devices are the usual storage devices, and the recharging is to be done as rapidly as possible, but specific norms are not established. As with an EM gun, there is a trade-off between storage and the need for a massive, intermittent draw from the main engine to recharge the storage devices. The faster the recharge rate, the greater the engine power and the less storage capacity required.

Lethality consumes power on two scales: a well established small scale for turret drive (50 hp maximum, 5 average) and a large scale for an EM gun (1,500 to 2,500 hp, depending on the assumed firing rate and available electrical storage). Of intermediate power requirement is the electrothermal cannon (ETC) at 200 to 500 hp. The actual power requirement for either of these guns entails a number of significant, but as yet undetermined, variables. Also, the useful reality of the EM gun is still in doubt as it remains under development as a practical device.

Both active armor and EM/ETC guns require some electrical storage along with assorted generation and control equipment. While the generation and control equipment space claim can largely be absorbed synergistically with an electric drive transmission system, the electrical storage consumes valuable interior space at the same time the increased power (and therefore

space) requirements for the armor and gun have also greatly increased. The need for quantum improvements in power density here is evident.

The above discussion focuses on the need for additional power leading to far more power dense powerpacks. Yet even in the absence of a need for additional power for an EM gun or for greater speed, the inevitable requirement for ever larger conventional guns and their bulky ammunition demands the conversion of propulsion space and weight to ammunition. This alone requires higher power densities in order to merely maintain mobility. While it is true that a modest additional space claim for the weapon can be accommodated by lengthening the vehicle (by modification or at design inception), there is a practical limit which will shortly be reached. Lengthening the vehicle adversely affects steering, requiring yet more power. It also adds weight to the vehicle due to additional hull weight, the above mentioned increase in power, additional road wheels and suspension, and track. At this time, vehicle weights are already considered marginally acceptable by the Army (e.g., for deployability; fuel economy; bridge passage; general on-road usage; and over soft terrain, wider track for higher flotation, being unacceptable).

3.5.2 Existing vehicles

3.5.2.1 Background

Owing to the post-Cold War drawdown, the Army will, of necessity, often execute modernization of the force more by the upgrading of existing types of vehicles than by the acquisition of entirely new systems. When improved survivability meant new and heavier conventional armor, this approach was largely impractical, and a new vehicle usually ensued. Now with appliqué, modular, reactive, and active armor, as well as active countermeasures, improved survivability can be readily achieved on existing vehicles, along with other system upgrades such as weapon, sensor, crew function, or safety. Upgrades may be made either to an existing assembly line operation or to existing vehicles brought back from the field. It is, of course, speculative to predict the future upgrade requirements and burdens on any given vehicle, but the example of the Bradley (M2) is illustrative. As originally fielded, the M2 was a 500-hp, 25-ton gross vehicle weight combat vehicle. As presently fielded, the M2A2 is a 600-hp, 32-ton vehicle that would

require 700 hp to match the mobility of its companion M1 (22 hp/ton). Further concepts at higher weights already are being discussed. Additional power would be required to incorporate any power-consuming mission packages such as active armor.

Similarly, the M1 has undergone weight increases due to the additional armor and a heavier gun and ammunition. Originally projected to be fielded at 60 tons, its 1,500-hp must now move 69.5 tons, and the M1A3 ("tank 1080") is projected to weigh 70 tons only because the 140-mm gun weight is compensated by a titanium turret, the value and cost of which is yet to be determined. Mobility has suffered both on- and off-road. Up to January 1995, an ETC gun was a candidate weapon for the M1A3, a weapon which would have added a considerable space and power burden to the already overweight and underpowered vehicle. At 40 percent of the hull volume, the propulsion system (while providing the necessary power) occupies critical space needed for the gun. With the ETC gun, any AIPS level power density providing 1,800 hp is needed to restore the original mobility, avoid the sacrifice of mobility to recharge the gun (over the 600-hour mission profile course), and provide space to the gun and its accoutrements. This vehicle could not be lengthened the required amount of 36 in. without an unacceptable weight increase to 73 tons and yet another 75 hp to cover the weight increase. Furthermore, the lengthened track will take the track length/width ratio from 1.61 to 1.93, making the vehicle essentially unsteerable.

These examples illustrate the anticipated weight growth of a vehicle over time and the impact of weapon upgrades on the vehicle interior, with the ensuing push on the propulsion system for both increased power delivery and reduced space claim.

3.5.2.2 An example of the M1 with increased hp/ton

The illustrative tabulation shown in TABLE 3-1 illustrates the gains that can be made by incorporating higher power density propulsion systems (HPDPS) into the existing M1. The basic vehicle would be unchanged, although as shown in the tabulation, weight would increase due to the increased weight of the higher horsepower propulsion system. To achieve the resulting higher vehicle speeds, active suspension would be required. Such changes would affect the power

requirement shown in Fig. 3-1, but their effect on total vehicle volume and weight is believed to be minimal. It is recognized that for transport or other practical reasons, it may be necessary to restrict weight. However, it should be noted that because of increased hp/ton, offsetting weight reductions via such techniques as active armor is also possible.

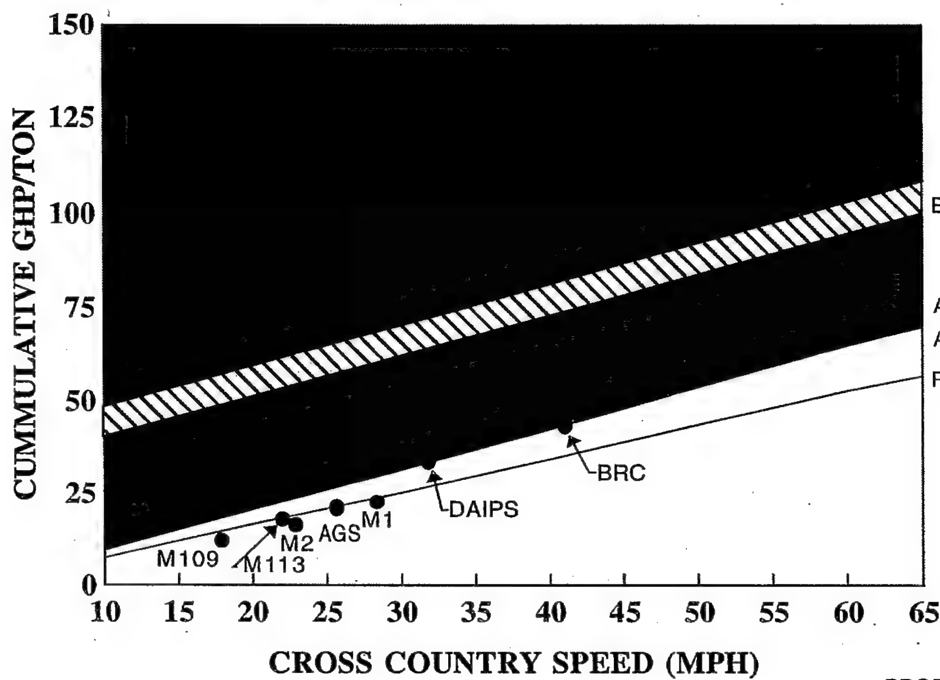
TABLE 3-1. Advantages of Incorporating HPDPS Into the Current M1 Vehicle

	AGT1500 Technology	dAIPS Technology	BRC Technology
System volume, cu. ft	291	291	291
Power density, hp/cu. ft	5.2	8.8	11.3
Horsepower	1,500	2,560	3,288
Weight, tons	68.0	73.4	75.9
hp/ton	22.1	35.0	43.3

The results of the analysis shown in TABLE 3-1 are plotted in Fig. 3-2 to show the resulting increase in vehicle speed. Figure 3-2 includes the data points of Fig. 3-1 but adds two new points, dAIPS and BRC, which correspond to the hp/ton values in the last row in TABLE 3-1. Note in Fig. 3-2 that in going to the dAIPS technology, some fraction of the increased power is required for active suspension, with the remainder available to increase vehicle speed. However, when going from dAIPS to BRC technology, almost all of the increased power is available to increase vehicle speed. Vehicle speed is increased from the current speed of approximately 28 mph to approximately 41 mph, an increase of approximately 46 percent.

The percentage increase in speed resulting from increased propulsion system power density is vehicle dependent. It is greater for vehicles whose current power systems are of lower power density. This is illustrated in TABLE 3-2 where markedly different percentage increase in maximum speed will be noted. It is obvious in TABLE 3-2 that vehicles with low power density propulsion systems benefit more by using higher power density systems than do vehicles already having moderate power density systems.

HP/TON VS. CROSS COUNTRY SPEED



* PROPULSION INCLUDES FIRE & ENVIRONMENTAL CONTROL

** EM GUN - TIME AVERAGED POWER FOR 5 SHOTS PER MINUTE

Figure 3-2. <u>hp/ton vs. cross-country speed</u>

TABLE 3-2. Advantages of Incorporating HPDPS Into Current Combat Vehicle Systems

		Current Technology		dAIPS Technology		BRC Technology		
Vehicle	Current Power Density, hp/cu. ft	hp/ton	CC* mph	hp/ton	CC mph	hp/ton	CC mph	% Inc. in Max. CC Speed†
M1	5.2	22.2	28	35.0	32	43.3	41	46
M2	4.3	18.2	23	34.9	32	43.4	41	78
AGS	4.1	22.2	26	43.4	42	53.7	51	96
M109	2.9	13.9	18	38.3	39	47.6	45	150
M113	2.8	20.7	22	55.4	50	68.1	58	163

* CC = Cross Country
† Versus current CC speed

3.5.3 New vehicles

Increasing the propulsion system power density allows the vehicle designer to design new vehicles that are shorter in length/height and lighter in weight. Estimates of savings must be for a specific vehicle with specific performance characteristics. TABLE 3-3 illustrates vehicle weight savings estimates compared to a nominal 60-ton vehicle using the AGT1500 propulsion system while keeping hp/ton nearly constant. The estimates assume constant vehicle propulsion cross-sectional area with all volume savings showing up in length reduction with consequent savings in vehicle weight. For a 60-ton vehicle--considering the currently perceived threat--top, side, floor, and skirt armor as well as track weight savings were estimated at 172 lb/in. of vehicle length reduction. For a constant hp/ton, this weight reduction means a reduction in the propulsion system horsepower required, as shown in TABLE 3-3.

The total vehicle weight savings numbers presented include both hull savings as well as the savings related to making the propulsion system more compact. Details and methodology of the reduction in length and weight savings analysis are presented in Section IX.3.9.3, Appendix IX, Volume II, TABLE IX-20. Using slightly different methodology, TABLES IX-15 through IX-19 illustrate savings when vehicle weight and hp/ton are varied.

TABLE 3-3. Example of Weight Reductions Made Possible by Incorporating HPDPS Into a Nominal 60-ton Future Vehicle Keeping hp/ton Constant

	AGT1500	dAIPS	BRC
Propulsion System hp	1,500	1,300	1,250
Vehicle Weight, tons	60	52.7	50.2
hp/ton	25	24.7	24.9
Total Weight Decrease, lb	Ref	14,612	19,595

3.6 The Need to Increase Survivability

The defense community intuitively believes that although the benefits cannot be easily measured or documented, increased hp/ton would be beneficial to vehicle survivability because of better performance of the activities listed below.

a. maneuverability (agility)
b. moving from firing position to firing position
c. moving to refuel and rearm
d. moving to reinforce
e. conducting flanking maneuvers
f. hit avoidance
g. dash to cover (reduce exposure time).

Figure 3-3 illustrates one attempt to quantify, from a survivability standpoint, the vehicle performance benefits of increased hp/ton. The terrain is typical of Germany, and the vehicles were Bradleys versus BMPs (Boevaya Mashina Pekhota infantry fighting vehicles). The Bradley (blue) vehicle was fitted with a laser warning device to detect when it was being targeted by a laser-guided system. The defenders (red) were in hull defilade. A survivability maneuver time was then determined that was associated with the laser line-of-sight and the time of flight for the missile. The maneuver time ranged from 6 to 24 seconds. The differences in survivability in going from 25 hp/ton [1.7 Loss Exchange Ratio (LER)] to 50 hp/ton (2.6 LER) seem small on

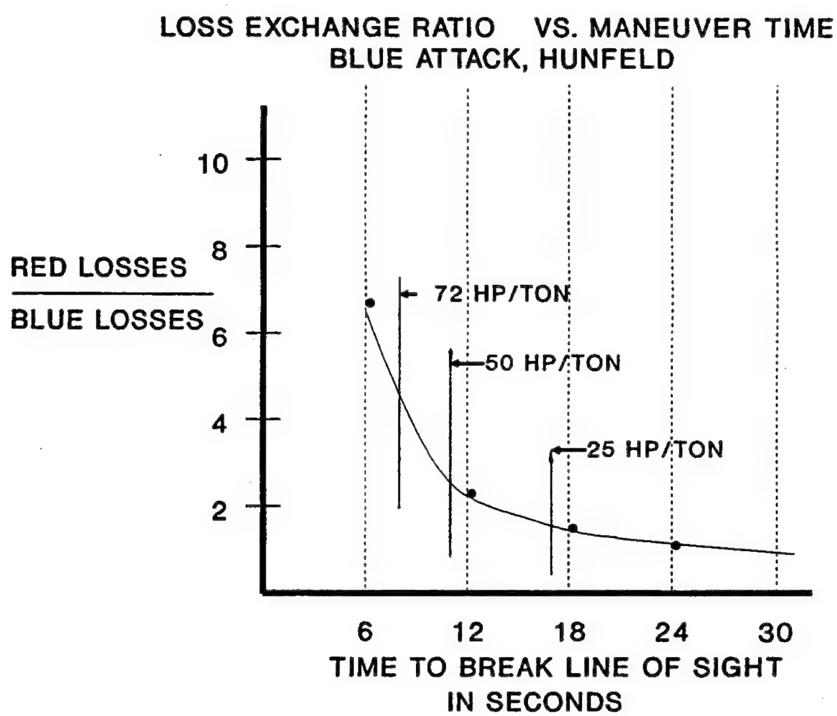


Figure 3-3. <u>The vehicle performance benefits of increased hp/ton</u>

this scale but are very significant in the battle analysis. Also note that the 50 hp/ton is just at the start of the rapid rise in survivability, i.e., additional unit increases will result in greater percentage increases in survivability.

Figure 3-4 presents an evaluation of the effect of vehicle size (i.e., cubic volume) on survivability for a baseline vehicle smaller than the M1 tank. The analysis was for two scenarios: Southwest Asia (SWA), with essentially flat desert terrain; and Northeast Asia (NEA), with more hills and vegetation. In the parametric analysis, a decrease of vehicle size by 25 percent resulted in a reduction of 34 and 18 percent blue dead in the SWA and NEA scenarios, respectively.

However, the increased flexibility in vehicle design resulting from increased power density can further increase survivability. A study has shown that a low profile Bradley vehicle (normal height of 117 in.) has survivability advantages, as illustrated in Fig. 3-5. As shown, for two different sensors, there is a significant improvement in survivability (35 percent) for a 25 percent height reduction. Increased propulsion system power density has the potential for lower vehicle height and hence, smaller silhouette and greater survivability, as well as increased flexibility for location of the propulsion system.

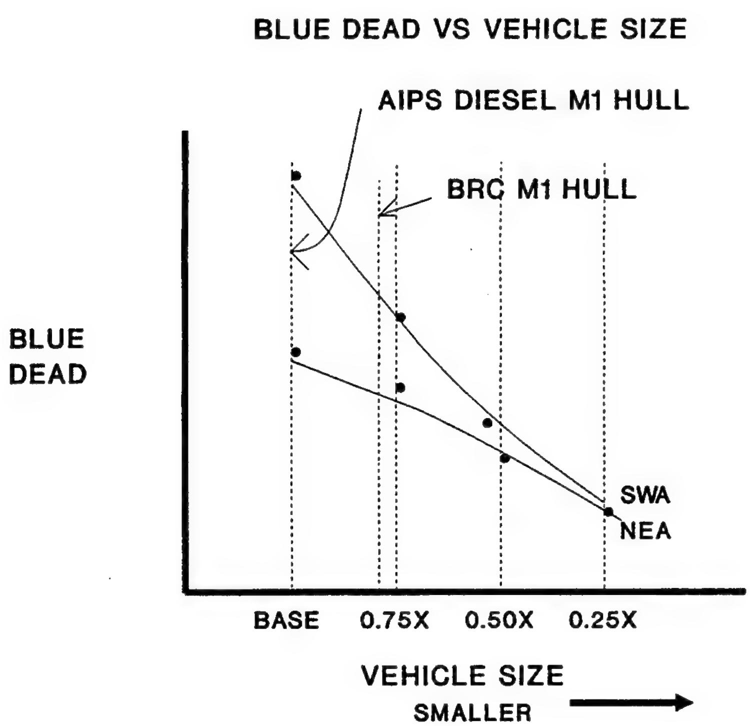


Figure 3-4. The effect of vehicle size on survivability for a baseline vehicle smaller than the M1 tank

3.7 Factors Affecting Development Strategy

The following factors should be considered when establishing a development strategy:

1. Major increases in both propulsion and auxiliary power may be needed for both new and existing vehicles if the U.S. is to remain internationally competitive.

2. There is a major potential for increasing the speed of existing vehicles by upgrading their propulsion system power density (refer to TABLES 3-1 and 3-2).

3. Survivability will be significantly increased as a result of these power increases.

There are three additional factors to keep in mind when considering development strategy:

4. The Army must provide funding if Army-unique requirements are to be met.

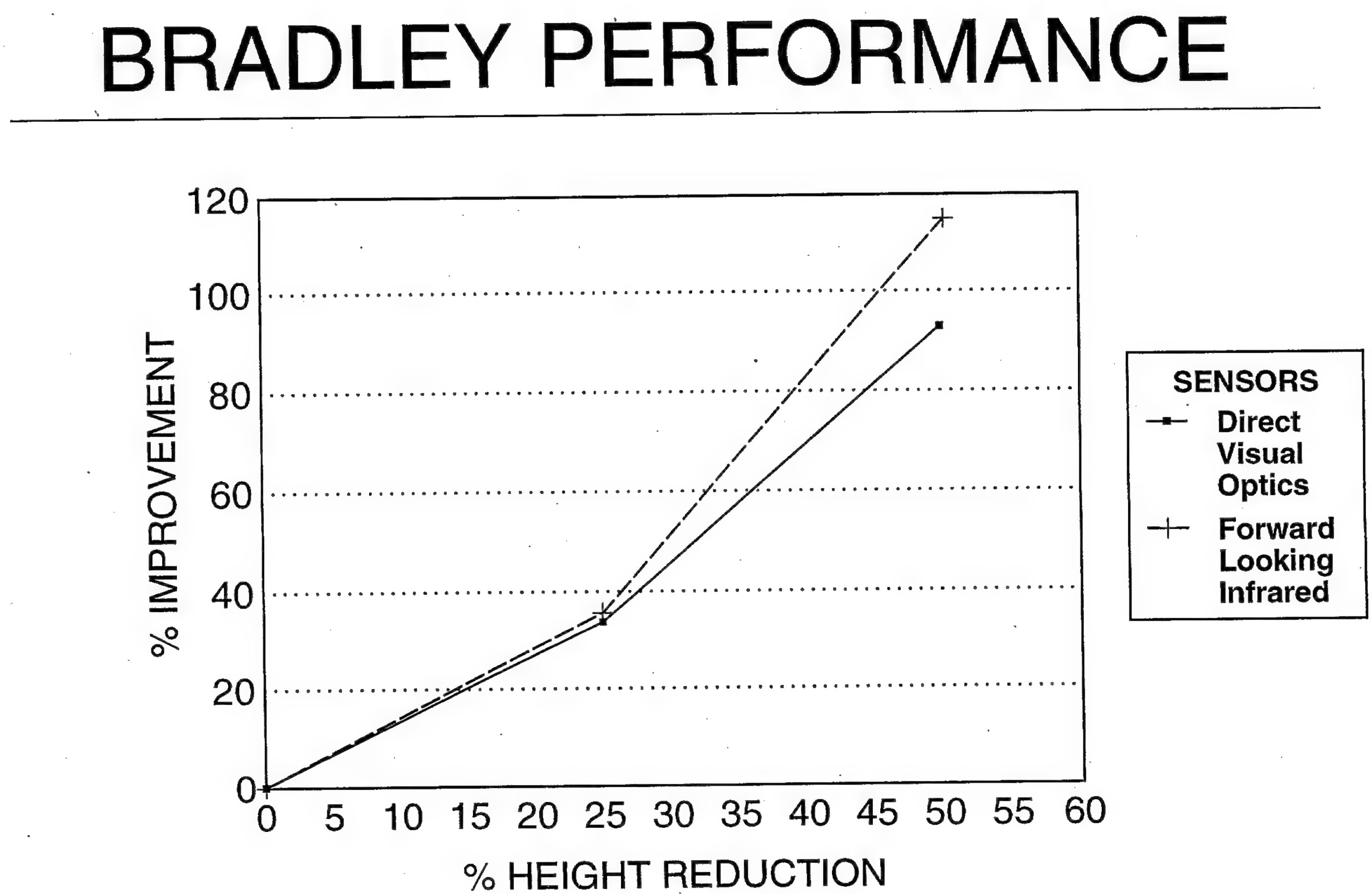


Figure 3-5. <u>Bradley performance critical dimension results</u>

5. Because of increased communications, technological developments spread rapidly throughout the entire world.

6. Being number two is a disaster when it comes to the battlefield.

3.8 The Development Strategy to Remain Number One

Since the gains resulting from increased propulsion system power density differ between existing and new vehicles, they will be discussed separately.

3.8.1 Retaining number one ranking for existing fighting vehicles

The rapid, worldwide spread of technology ensures near-term use of AGT1500 technology, and soon, AIPS-level of technology, in competing international combat vehicles. When this happens, U.S. combat vehicles will no longer be number one but merely one of the competitors. It is imprudent to assume that either AGT1500 or AIPS-level technology will remain the number one technology for long!

It has previously been established that significant performance and weaponry gains can be achieved if the BRC technology is developed. BRC technology will only be readily available if research and development is started now. If existing vehicles are to be upgraded to extend their useful life, they may only be competitive if the BRC technology is developed and used. Failure to initiate the BRC-recommended research program immediately and to carry it out on a timely basis over the next decade may mean that the U.S. will no longer retain its number one rating.

3.8.2 Ensuring continuation of number one ranking for new vehicles

Higher propulsion system power density is a desirable attribute for both existing and new vehicles. However, for new vehicles in the design stage, there is flexibility in both vehicle volume and arrangement that is not present in existing vehicles.

Also, in designing a new vehicle, there is an inherent tendency to think in terms of today's capabilities rather than future requirements. In peacetime, the life of combat vehicles is long. Thus, the capabilities of new vehicles must consider long-term performance needs as well as current needs.

The three attributes of new vehicles that need to be collectively optimized are deployability, lethality, and survivability. However, there is a design conflict between these attributes. Deployability is always optimum with a small, light vehicle, but a small, light vehicle is not inevitably optimum from a lethality and survivability standpoint.

A light, high-power density propulsion system helps to minimize this conflict. It is true that during the design process, vehicle size can be increased, resulting in a heavier vehicle. For small power increases, this trade-off may be acceptable, but the larger the power increase, the less acceptable the trade-off. Determining the optimum trade-off is not simple or easy.

Fortunately, it is not necessary to evaluate the optimum trade-off point. As previously shown, for existing vehicles the benefits of increasing propulsion system power density are compelling and persuasive, and by themselves, justify development of propulsion systems with increased power density. This same technology is applicable to new vehicles and therefore, synergistic between new and existing vehicles. This synergy permits spreading development costs across both existing and new vehicles with a resulting lower cost per vehicle.

3.9 Summary

1. Significant achievements in propulsion system power density are achievable.

2. Increased power density propulsion systems can provide the following:

    a. dramatic increases in maximum vehicle speed;

    b. increased survivability;

c. greater design flexibility; and

d. active defense and electromagnetic gun capabilities in existing vehicles as well as new vehicles.

3. New propulsion technology development cost can be amortized over both new vehicle applications and upgrading of existing vehicles.

4. ACHIEVING HIGHER POWER DENSITY PROPULSION SYSTEMS – EVOLUTION OR REVOLUTION

Higher power density (HPD) can come from revolutionary or evolutionary developments at either the system or component level, as well as combinations of the two. Revolutionary gains could come either from markedly improved integration of components or from introduction of a new revolutionary system. The HPD of both dAIPS and tAIPS resulted in a considerable part from improved component integration. Consequently, while there is still some room for improved integration, any future integration improvements would likely be evolutionary rather than revolutionary.

The only revolutionary system approach envisioned by the BRC would be use of a fuel cell. Current fuel cells would be extremely bulky and are limited to using hydrogen, either stored as a fuel or obtained from processing a hydrogen-containing fuel. It was the judgment of the BRC that in the foreseeable future, combat vehicle propulsion systems would use internal combustion engines and there would be no change to a revolutionary propulsion system.

However, the BRC did judge that there was a significant potential for revolutionary component changes. For example, two engine arrangements (the rotary engine and the Caterpillar Compact Diesel) minimize crank case volume, which increases engine compactness. Both have inherent trade-offs. In the transmission area, the increasing demand for non-propulsion-related electrical energy has increased interest in electrical propulsion, which would mean major changes in the transmission portion of the system.

In general, it takes more than a decade to bring a revolutionary development to the experimental prototype stage. Because of this, and because the BRC felt it was important that TACOM continue to be aware of and in contact with revolutionary developments, the BRC recommends that some fraction (10 to 25 percent) of its available research funds be used for research that would come to fruition in longer than a decade.

5. PERFORMANCE REQUIREMENTS PECULIAR TO COMBAT VEHICLE PROPULSION SYSTEMS

It is obvious that the optimization of a propulsion system depends upon the performance requirements for the system. A system optimized for 100-percent full-power operation would have a different configuration than a system optimized for 10-percent full-power operation and 90-percent low-power operation.

As discussed in more detail in Section V.2, Appendix V, Volume II, the performance requirements for combat vehicle propulsion systems are considerably different from the performance requirements of commercial propulsion systems and must be taken into account in optimizing the system. The areas in which there are major differences include the following:

Duty cycle – The combat vehicle duty cycle is heavily weighted toward low-load conditions in contrast to the high-load cycle characteristic of heavy-duty, over-the-road commercial trucks and material haulers.

Extremes of operating conditions – Since the location of future hostilities is not known, combat vehicles are required to operate at ambient extremes (e.g., –60 to +120°F) and terrain extremes (e.g., paved roads to cross country; snow, ice, sand, and mud). The capability to operate on a wide variety of fuels is valued.

Armor enclosure – For combat vehicles, the entire propulsion system is enclosed in armor with ballistic grilles for air inlet and outlet. As much as 10 to 15 percent of the propulsion system power may be required for powering cooling system fans.

Reliability versus durability – The inability to operate at a critical moment may be fatal. Furthermore, during combat, the lifetime of a combat vehicle is measured in the tens to hundreds of miles. Even in peacetime, combat vehicles cover less than 1,000 miles per year whereas commercial trucks accumulate up to 250,000 miles annually (Section V.2.10, Appendix V, Volume II).

6. OPTIMIZING COMBAT VEHICLE PROPULSION SYSTEMS

6.1 The Combat Vehicle Propulsion System

The heart of the combat vehicle propulsion system is, of course, the engine. For fuel fire safety and other reasons, only diesel engines or gas turbines are currently used in combat vehicles. The diesel engine uses heat of compression to ignite the fuel when it is introduced at high pressure (10,000 to 20,000 psi or higher) as the piston approaches top center. This means that the diesel must, and does, use high compression ratios.

The greater the mass of air in the cylinder, either because of greater cylinder size or increased air density, the more fuel can be burned and, consequently, greater power achieved. Increasing cylinder size results in a less compact system. Thus, diesel engines use a more volume compact turbocharger (exhaust-gas-driven turbine driving an air compressor) to increase the mass of air in the cylinder.

The variation, with speed, of the characteristics of the diesel engine differ from those of the turbocharger. In addition, as the vehicle traverses different terrains, the wheel speed and torque needed by the vehicle differ from the engine output. Consequently, a transmission is needed to match these differing engine, turbocharger, and vehicle needs and characteristics. During acceleration or with load changes, engine and turbocharger speed variations will be needed to match vehicle needs; there, inertia then becomes a factor.

The engine needs outside air for combustion. In addition, the engine, the transmission, and the compression-heated air from the turbochargers require cooling by outside air. Because of the dusty environment, this air must be cleaned.

Cooling system fans, absorbing as much as 10 to 15 percent of the engine output, are required to drive air through ballistic grilles and heat exchangers. Also, fuel tanks and batteries are needed.

It is clear from the above that the combat vehicle propulsion system is complex with many interactions between components. TABLE 9-1 in Appendix 9 of this volume shows the relative volume requirements of these components for different systems. Optimizing this complex system to meet power and fuel consumption requirements while occupying minimum volume with minimum weight is not a simple matter.

6.2 The Need for a Propulsion System Simulation Program

The primary objective of the BRC recommended research is to achieve a more compact powerplant system. It follows that we are trying to optimize a multi-interactive component system for maximum volume and weight compactness. The interaction between powerplant components is complex and significant. For example, if intercooling were not used, the system volume allocated to air handling would be reduced, but higher manifold pressures would be required to maintain the same mass airflow rate. Higher manifold pressures would affect the turbocharger and engine. Without a series of design studies, system optimization from a power density perspective is difficult to achieve. As another example, system stoichiometric combustion at full load could be achieved by lean combustion in the cylinder of a smaller displacement engine followed, at full load, by subsequent combustion in the partially vitiated exhaust to drive a turbine located in the exhaust. Full-load fuel economy would be poor but, because there is little full-load operation in combat vehicles, a more compact overall system might result. Other examples of component interaction are given in Section VI.1, Appendix VI, Volume II.

Optimizing any multicomponent system is difficult and is best approached through the use of as-accurate-as-possible analytical models. As indicated in Section VI.1, Appendix VI, Volume II, available commercial powerplant system models have different optimization criteria. TACOM has not yet developed a useful, detailed system model. It is the judgment of the BRC that an improved combat vehicle propulsion system model is needed and that this model should be used to analyze proposed changes and configurations as an aid in guiding future research.

7. THE BASELINE FOR JUDGING IMPROVEMENTS IN PROPULSION SYSTEM COMPACTNESS

Several powerplant systems could be used for baseline technology. One comparison would be a system in production and used on existing vehicles. One example would be the AGT1500 powerpack. Another example would be the Bradley powerplant system with the Cummins diesel VTA-903, which produces 600 hp, is in production, and has a volume of 135 cu. ft. Yet another system would be the German powerpack with MTU 883 engine, which is in production and has a volume of 215 cu. ft for 1,500 hp. Comparisons could also be made with systems still in the development stage. The dAIPS, at an experimental prototype stage with not all goals met, has a volume of 170 cu. ft for 1,500 hp.

In most cases, the dAIPS engine was selected for baseline technology purposes because it is the most advanced intermittent combustion engine on which the Army has conducted initial laboratory demonstration. Further, it is designed to power a main battle tank (nominal 1,500 hp, 60-ton heavy weight class) and is the most crucial vehicle in the Army combat fleet. Section VII.1, Appendix VII, Volume II presents detailed data on the characteristics of dAIPS and other propulsion systems. The dAIPS was tested in a Component Advanced Technology Test Bed tank at TACOM.

8. RESEARCH RECOMMENDATIONS

8.1 Philosophy Followed in Making Recommendations

8.1.1 Recommendation philosophy

Appendix 9, Volume I summarizes and Appendix IX, Volume II presents in detail all BRC suggestions considered for specific research projects to improve the performance of the powerplant components and fluids used in the powerplant system. However, especially in these times of limited resources, it is obvious that not all of these suggestions can or should be undertaken.

Also, it is egotistical for the BRC to make detailed research recommendations to cover a ten-year period. Therefore, the BRC concluded that it should recommend broad research thrusts, with TACOM determining over the decade the specific details, utilizing the approaches suggested in the appendices, where appropriate.

Consequently, the BRC recommendations presented below suggest broad areas in which research should be pursued, but the task of specifying detailed research goals is left to TACOM. In addition, brief comments will be made on some of the criteria for selecting specific projects and the time frame TACOM should consider.

8.1.2 Nontechnical considerations

In addition to technical criteria such as benefit/cost and probability of accomplishment, two additional considerations should be used by TACOM in selecting specific projects. The first consideration: Is this a research project, necessary for TACOM to achieve its objectives, that will not be undertaken by the commercial industry? The second consideration: What is the possibility of synergistic funding, i.e., is there enough industry need for this project that it could be partially funded by industry participants? In view of the current push for "dual use" technology

development, synergistic funding arrangements are encouraged and should be enumerated in any TACOM request for proposals.

8.1.3 Time frame for recommended research

The charge to the BRC was to recommend research that would lead to a more compact, experimental prototype engine system by the end of the next decade. While the BRC felt that a decade was a reasonable time frame, it also judged that it was not in the best interests of the Army to limit all of its research to this time frame. Consequently, as indicated in Section 4, Volume I, the BRC recommends that 10 to 25 percent of available funds be used for projects that will not necessarily come to experimental prototype fruition in the next decade.

8.2 Recommendations

8.2.1 Priority considerations

The purpose of the recommended research projects is to achieve a more compact powerplant system. It follows, then, that consideration and priority should be given to approaches that affect a large fraction of the powerplant system as opposed to those that affect only one of the components.

8.2.2 Propulsion system simulation

TACOM should accelerate development of an improved propulsion system simulation program having sufficient detail that it will be useful for powerplant system optimization. This program is needed in order to point the direction toward increasing powerplant system compactness and to minimize experimentation. Since this simulation would be extremely useful in evaluating proposed configurations, it should be developed as soon as possible. During the course of the BRC study, considerable propulsion system simulation efforts have been initiated. The results of these simulation efforts should be considered by TACOM, on a continuing basis, to determine the extent of additional propulsion system simulation required and to guide future research

efforts. Since output from these simulation efforts are not yet available, the BRC decided to recommend four broad areas of intermittent combustion engine research, in priority order, as stated in Sections 8.2.3, 8.2.4, 8.2.5, and 8.2.6.

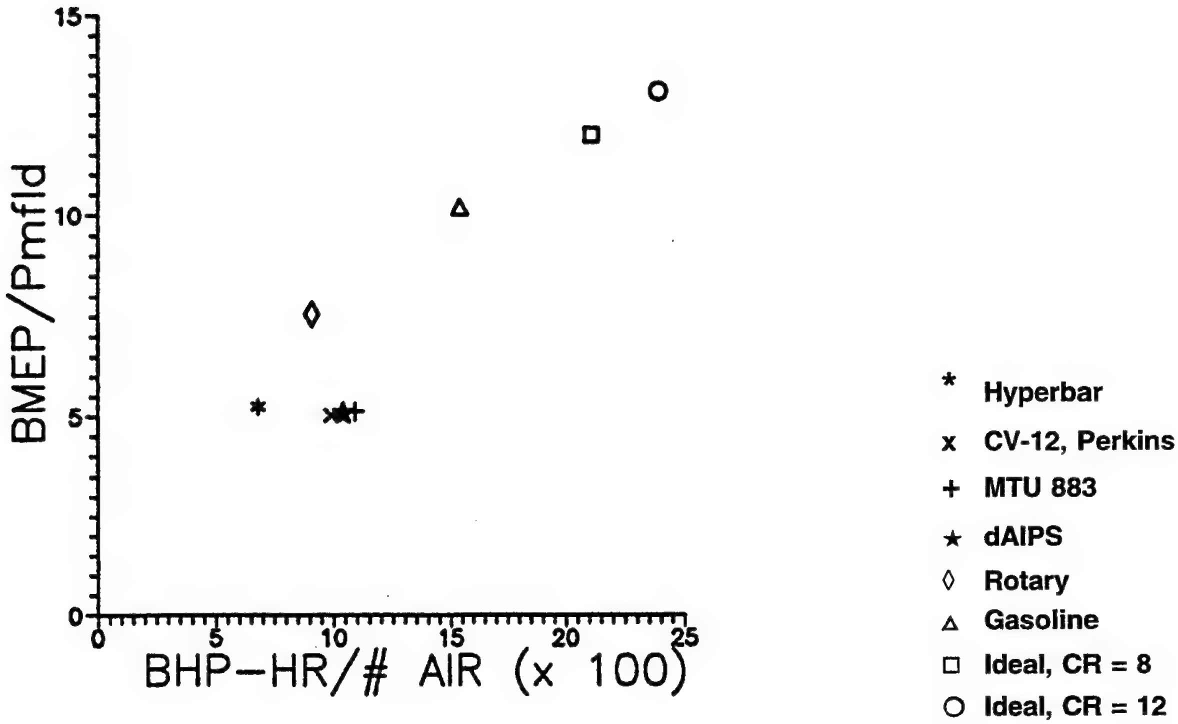
8.2.3 More effective use of displacement and combustion air

TACOM should conduct research necessary to better utilize engine air and displacement. Powerplant system compactness is affected by work per unit displacement and work per unit mass of engine airflow--this is the inverse of brake specific air consumption (BSAC), mass of air per unit work. Increasing work per unit displacement decreases engine size; increasing work per unit mass of air decreases the size of the engine, turbocharger, charge air heat exchangers, and air filter(s).

The engine parameter BMEP has the units of pressure, i.e., force/length squared. However, when multiplied by length/length, the units become work per unit volume, i.e., force × (length/length cubed). Also, if BMEP is divided by inlet manifold pressure, the ratio is dimensionless. Assuming the same inlet manifold air temperature, density is proportional to pressure. This enables comparisons to be made between engines having different manifold densities.

Equation 5b, Appendix IX, Volume II, Section IX.2.2.2 mathematically relates BMEP/Pmfld (more precisely, density) and 1/BSAC. Figure 8-1 graphically presents the results of ideal cycle analysis and experimental data from five different combat engines, a gasoline engine, and the results of two ideal cycle calculations. The tabulation below Fig. 8-1 presents selected characterizing and performance parameters. Note the wide variation in these factors.

The gasoline engine is not shown to suggest that gasoline should be used as a fuel but rather to show that significant gains could be achieved if the diesel could operate significantly closer to stoichiometric combustion. The gasoline engine includes most of the real gas effects and some of the heat transfer effects resulting from stoichiometric combustion. It does not include the effects of heavier engine components required for supercharged diesel operation.



Engine	Disp., in.^{3}	CR	Max. Power rpm	Max. Power BMEP	Pmfld ATM	bhp
Hyperbar	1,005	7.8	2,500	462	6.0	1,470
CV-12, Perkins	1,593	12.3	2,400	311	4.0	1,500
MTU 883	1,664	14.0	3,000	236	3.1	1,475
dAIPS	1,682	14.5	2,600	262	3.5	1,450
Rotary	700	9.0	4,500	189	1.7	1,500
Gasoline	355	9.0	8,000	150	1	538
Ideal F/A	N/A	8.0	N/A	176	1	N/A
Ideal F/A	N/A	12.0	N/A	193	1	N/A

Figure 8-1. Air and displacement utilization

The last two engines are ideal "paper" engines computed using fuel and air as the working fluid and having compression ratios of 8 and 12 as indicated.

It seems clear from Fig. 8-1 that there is considerable potential gain in system compactness by moving closer to stoichiometric combustion, especially since use of stoichiometric combustion affects a high percentage of the volume of the powerplant system. The difficulties in achieving stoichiometric combustion in the cylinder should not be minimized, however. The problems of mixing air and fuel, higher cylinder and exhaust operating temperatures, higher cylinder

pressures, and transient operation are formidable. It should be noted that there are arrangements such as an "afterburner" ahead of the exit turbine, used only at full power, that can produce additional power and a stoichiometric exhaust, but generally with increased fuel consumption. The propulsion system simulation program recommended above would be very helpful in sorting out the merit of this and other different arrangements.

8.2.4 Increase displacement rate

TACOM should conduct the research necessary to increase the engine displacement rate. Displacement rate is the number of power strokes per unit displacement per unit time. As indicated previously, increasing the displacement rate may increase system compactness. As indicated in Appendix IX, Volume II, for certain fixed parameters, the most efficient way to gain this increase is to increase engine rpm, decrease cylinder bore, and possibly increase the number of cylinders. Again, there are problems to be overcome. In general, increasing rpm increases inertia forces and friction. As is true with stoichiometric combustion, as the cylinder fuel burning rate is increased, the previously mentioned thermal problems result, as well as potential matching problems with the drive train.

8.2.5 Increase manifold air density

TACOM should conduct the research necessary to increase manifold air density. Another approach to increasing engine compactness, again assuming the same effectiveness of use of engine displacement and air, is to increase manifold air density either by increasing manifold air pressure or, if available turbocharger output permits it, by expansion cooling of manifold air. However, increased manifold pressure increases peak cylinder pressure which in turn increases mechanical loading. It seems increasingly feasible[1] to significantly reduce peak cylinder pressure by the use of fuel injection rate shaping and multiple injections. This reduction in cylinder pressure will permit higher supercharging with the same maximum engine stress levels.

[1] Nehmer, D.A. and Reitz, R.D. "Measurement of the Effect of Injection Rate and Split Injections on Diesel Engine Soot and NOx Emissions," Army Engine Research Center, University of Wisconsin-Madison, Paper No. 940668, presented at the SAE Congress, February 1994.

The problems are in many ways similar to the previous approaches with an additional burden placed upon the turbocharger and charge air cooler(s), if used. Again, the volume reduction is primarily in the engine portion of the system.

8.2.6 Thermal management

Increasing either brake mean effective pressure (BMEP) or piston speed results in higher rates of heat release with consequent increases in cylinder temperatures and, unless thermal resistance is increased, greater heat loss and load on the cooling system. The efforts of TACOM and others during the past decade in the area of in-cylinder ceramic insulation have markedly decreased heat rejection rates per unit of work out. Regulated local cooling can aid significantly in controlling thermal loading with reduced total heat rejection. Continuation of these past efforts will be essential if higher rates of heat release are to be achieved while still maintaining or even lowering heat rejection rates per unit of work out.

8.2.7 Long-range research

TACOM should continue to allocate a small fraction of available research funds for research projects that may not come to experimental prototype fruition in the next decade. Section 4, Volume I presents the rationale for this recommendation. Continuing review of these projects with use or abandonment of findings will be essential.

8.2.8 Electric drive study

In addition to the aforementioned four thrust areas of research, TACOM should conduct a study of the implications of electric drive on the optimum propulsion system configuration. Because of the increasing need for auxiliary electric power and other considerations, there is increasing interest in the use of electric drive for combat vehicles. Insofar as the BRC knows, there has not been a comprehensive study of the optimum powerplant and electric propulsion system configuration for the operating regime of combat vehicles. Such information is essential in judging research needed to achieve maximum electric propulsion system compactness. Again,

this information should be obtained as soon as possible since it is essential in making decisions regarding needed electric propulsion research.

9. RESEARCH SUGGESTIONS CONSIDERED

The material for this section is tabulated in Appendix 9 of this volume (Volume I). An even more detailed tabulation of these research suggestions is presented in Appendix IX, Volume II.

10. ACCOMPLISHING BRC RESEARCH RECOMMENDATIONS

10.1 General Approach

The BRC judges it best for TACOM to specify desired goals in its implementation of this report. This approach of specifying desired goals utilizes the expertise and background of the offerors who submit proposals in response to any TACOM request for proposal in achieving the desired goals rather than depending solely on the expertise of TACOM to specify the research needed. The recommendations listed below follow this approach.

10.2 System Compactness Analysis Goal

One of the first priorities should be to develop a useful propulsion system simulation program capable of evaluating and optimizing proposed configurations with acceptable accuracy. As suggested in Section 8.2.1, such a program should then be used to study and optimize the compactness that could be achieved by different configurations. There would be a considerable enhancement of TACOM capabilities and understanding if this were an in-house program. **While an improved simulation is definitely needed for confirmation and optimization, the BRC is confident in recommending the following initial performance goals.**

10.3 Performance Goals

The BRC recommends that TACOM solicit proposals, that in ten years, would result in an experimental prototype, multicylinder engine in the 1,000 to 1,500 hp range, capable of meeting the full-power performance goals listed below. Achievement of the performance goals listed below should enable the BRC component and system goals shown in Appendix 9, TABLE 9-1 of this volume to be exceeded. It is essential to understand that while individual goals may be reached, the real challenge is to demonstrate all of the following goals in the same engine:

- a bhp/cu. in. displacement of 1.5 with acceptable smoke and starting capabilities;
- total heat rejection no greater than 18 Btu/bhp-min;
- battlefield day fuel consumption of 235 gallons, compared with dAIPS goal of 250 gallons;
- use of engine oil as both engine coolant and transmission fluid with a common sump, which would result in a volume reduction as well as improved maintenance and logistic considerations; and
- reduction of required cooling fan hp from dAIPS by 25 percent at a heat rejection rate of 18 Btu/bhp-min.

Accomplishment of these individual goals will aid in achieving the overall goals of

- a decrease in engine volume by 35 percent versus the dAIPS engine, and
- a decrease in propulsion system volume by 22 percent versus the entire dAIPS.

It is expected that results from both the system simulation study and the electric drive study would become available early in this ten-year development program and that any applicable results would be incorporated into this recommended prototype development in a timely manner.

10.4 Research Coming Into Fruition in Longer Than a Decade

10.4.1 General approach

As mentioned in Section 8.1.3, the BRC recommends that a small fraction of TACOM research funds continue to be allocated to research coming into fruition in more than a decade. This objective implies that the research will encompass new and different approaches as opposed to conventional advanced engineering research and development. If the approaches are new, they cannot be evaluated until they are proposed.

At least three broad classifications of long-term studies can be identified. While examples will be given to illustrate the classification, the BRC has not evaluated the merit of any of the illustrations.

10.4.2 Major reductions in the volume of a system component

For example, the developers of the Rotary, Randcam, and Caterpillar Compact Diesel engines all claim significant reduction in engine volume. As another example, heat exchanger size could be reduced if engine heat rejection could be reduced.

10.4.3 Mechanism changes that would provide improved operating characteristics and thus increase compactness

Examples would be variable valve timing, variable compression ratio, and variable geometry turbocharger.

10.4.4 Fundamental studies that would improve the operating characteristics or range of a component of the system

For example, tribology (i.e., lubrication, friction, wear), particularly at high temperature, is a problem in all high output engines. Also, improved materials are typically key to improved performance.

APPENDIX 2

Technical Support Provided to the Blue Ribbon Committee

(Note: Appendices 1, 3-8 and 10 are not used.)

APPENDIX 2

TECHNICAL SUPPORT PROVIDED TO THE BLUE RIBBON COMMITTEE

Name	Organization
Dr. Robert E. Bill	Army Research Laboratory, Propulsion Directorate, NASA Lewis Research Center
Dr. Walter Bryzik	TARDEC Propulsion Research
Mr. George Cheklich	TFLRF (SwRI) Propulsion Consultant
Mr. Maurice LePera	TARDEC Belvoir Fuels and Lubricants
Mr. John Lewis	TARDEC Advanced Concepts
Mr. Lynn Martin	TARDEC Advanced Concepts
Dr. Richard E. McClelland	TARDEC Research Business Group
Mr. Charles Miller	TRADOC Analysis Command
Dr. Richard Munt	TARDEC Propulsion Research
Mr. Ernest Schwarz	TARDEC Propulsion Research
Mr. Wayne K. Wheelock	TARDEC Director

APPENDIX 9

Research Suggestions Considered

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APPENDIX 9

9. RESEARCH SUGGESTIONS CONSIDERED

9.1 Integration Versus Component Development

Among other things, dAIPS paid particular attention to integration; only 10 percent of the system is unused. Since unused space will never go to zero, there is an upper limit on the gains to be made. However, there is some potential for additional integration. For example, if the same lubricating fluid is used in the engine and transmission, there could be a common sump; there are individual sumps in dAIPS.

9.2 Improved Compactness of Individual Components

9.2.1 General comments

There is interaction between components that must be taken into account when evaluating compactness improvements. The recommended propulsion system simulation should be helpful in this evaluation.

Also, propulsion volume is largely driven by maximum power requirements, which are generally directly proportional to maximum power airflow. In addition, full-power heat rejection requirements drive the cooling system volume and the power required to drive cooling fans and pumps. In order to reduce the <u>system</u> volume, therefore, one must consider reducing volume requirements associated with maximum power.

A major factor in maximum power volume requirements is the "steady-state" airflow. Section 8.2.2 discusses reduction of required airflow. However, in actuality, acceptable transient response generally dictates "larger-than-steady-state" engine displacement. Consequently, if the "steady-flow" portion of the air-handling machinery is able to provide better transient response, it could help to decrease engine displacement and the size of the other parts of the air-handling machinery.

9.2.2 Engine

Many factors affect engine compactness. Appendix IX, Volume II indicates many of these factors and the needed research. To summarize, within limits for the same piston speed, fuel-air ratio, strokes/cycle and fuel consumption, a smaller bore engine is more compact than a larger bore engine. For the same effectiveness, maximum power is determined by displacement rate and manifold air density. This relationship suggests increasing displacement rate by some combination of smaller bore and stroke and increased rpm and/or number of cylinders and increasing manifold air density. It should be noted that any of these approaches will result in a larger amount of fuel being burned per unit displacement per unit time. This increased consumption will inevitably result in higher cylinder temperatures. Since technology is currently nearing the upper temperature limit of many in-cylinder components, this increased displacement rate will undoubtedly require research to accomplish.

9.2.3 Steady-flow machinery

9.2.3.1 Turbochargers

Increased turbocharger efficiency reduces the heat rejection requirement to the aftercooler. Also, as indicated previously, improved turbocharger response in transient conditions may result in some reduction in engine displacement. The requirement for a wide operating range for high-pressure ratio turbochargers can be reduced by electric drive or an increased number of gears in the transmission. If increased combustion air utilization is successful, exhaust temperatures will be higher, and new materials will be required. New turbocharger materials resulting in a lower inertia turbocharger would improve transient response. Much of the needed research will have direct commercial applications.

Intake manifold density has a proportional effect on the specific power achievable from an engine. It is therefore recommended that methods of increasing the maximum pressure ratio and map width of turbocharger compressors be pursued. This goal can be best achieved by increasing the maximum permissible speed of the compressor and turbine wheels, which are now limited

by the maximum strength of the material. Ceramic compressor and turbine wheels have significant advantages in this respect; they have lower inertia for better turbocharger response, do not lose strength at higher temperature, and can tolerate high tip speeds. Ceramic turbine wheels are in production, but some work is still required on ceramic compressor wheels.

The dAIPS propulsion unit has the requirement of accelerating from idle to full power in two seconds. This requirement is very severe as the turbocharger cannot accelerate fast enough to provide sufficient air to support combustion. The result is excessive smoke during accelerations to the extent that the dAIPS contractor has introduced a particulate trap to the dAIPS engine to reduce the black smoke signature. The particulate trap, together with the necessary equipment to regenerate it, takes up significant space. The particulate trap does not improve engine acceleration; it only hides the results of poor turbocharger response. More elegant solutions to this problem would be the use of low inertia turbochargers with ceramic wheels: variable geometry, wastegated turbochargers; powered turbochargers; and the use of a supplemental supercharger to operate at low speed and during accelerations when the turbocharger is ineffective. A variable displacement mechanical supercharger is ideally suited to this application. When the turbocharger is functioning as required, the displacement of the supercharger can be turned to zero so its effects are neutralized.

9.2.3.2 Heat exchangers

Using high-temperature coolant is the most effective way of reducing heat exchanger size. This use of high-temperature coolant has already been done on the dAIPS project. Small improvements may still be possible in the detailed design of the heat exchanger, but the most gain will be made in reducing the dust contamination of the air side of the heat exchangers. Possibilities include: investigating the flow conditions and fin designs that inhibit dust accumulation; or even filtering the cooling air through course vortex tubes to remove the dust.

The air from the compressor is aftercooled from 230°C down to 138°C by the high-temperature oil coolant in the dAIPS engine. If an air-air aftercooler were used instead, then only one step of heat transfer rather than two would take place, and so the total heat exchanger volume could

be reduced. In addition, the temperature of the aftercooled charge air could be significantly less, permitting an increase in engine power from increased charge air density.

9.2.3.3 Air cleaners

The most significant potential advance in air filtration appears to be in pressure-side filtration. Pressure-side filtration is the placement of the barrier filter downstream of the turbocharger compressor. This placement has significant advantages.

- A given blockage at the pressure-side filter causes less engine gas exchange loss (pumping loss) than the same restriction would as a barrier filter upstream of the compressor. This decreased loss is because pressure loss over an orifice is inversely proportional to charge density.

- The filter can be made smaller than the conventional barrier filter by a factor of the increase in charge density. The pressure-side filter may therefore be less than half the size of the conventional barrier filter.

Pressure-side filtration does require efficient prefiltration upstream of the turbocharger compressor to prevent compressor wheel erosion. The vortex tubes in the prefilters can remove particles over 5 micrometers in diameter. These filters are about 95 percent effective. It is not clear how fast a compressor wheel will erode when subjected to particles not removed by the prefilter. However, there are various countermeasures to wheel erosion such as the use of ceramic wheels or ceramic-coated wheels. The life expectancy of the combat engine is not as long as that of a heavy-duty commercial engine, so the problem of wheel erosion may be overstated.

Current research efforts to increase efficiency of precleaner vortex tubes would reduce compressor wheel erosion and also permit smaller pressure-side barrier filters with longer filter change out periods. Such tubes remove particles over 2 micrometers in diameter.

It is recommended that pressure-side filtration and the necessary associated technologies be further investigated by TACOM.

9.2.3.4 Fans

The cooling air fans consume as much as 15 percent of the power output of the engine. There may be additional incremental gain in the design efficiency of the fans themselves, but most gains in power and space savings appear to be in the fan drives and in the fan control systems that turn off the fans when they are not required.

9.2.4 Transmissions

9.2.4.1 Mechanical

Since mechanical transmission design is an established technology, the primary requirement for future combat vehicle propulsion systems is to design a transmission as an integral part of every engine design to achieve maximum propulsion system compactness and matched for best performance and low fuel consumption.

To accommodate higher engine speeds and to utilize these speeds in the transmission, much higher energy-absorbing clutch material must be developed. This material must be capable of operation at high-temperature conditions in the transmission.

Another area in the mechanical transmission needing research is a high-temperature oil that can be used in both the engine and transmission, utilizing a common sump.

These items will result in the most compact powerpack possible. An additional 20-percent reduction in transmission volume can be expected by advances in and application of the aforementioned transmission technologies.

9.2.4.2 Electric

Because of the increasing use of auxiliary electric power in future vehicles (400 to 600 hp) and because of other considerations such as rear access and flexibility in arrangement of different components for optimum space management, there is an increasing interest in electric drive propulsion for tracked and wheeled vehicles. Thus far, the Army's programs have been limited to technology surveys, identification of component research needs, and studies that have provided projections on potential applications of electric drives, taking into consideration the auxiliary uses of electric power in future vehicles, and some initial vehicle demonstrations. Although some of these projections need substantiation through further verification testing or prototypes, it should be recognized that electric traction motors are capable of producing the torques required to meet or exceed the acceleration and gradeability currently achievable with the mechanical drive systems. In addition to the system optimization study for electric transmission vehicles discussed in Section 8.2.5, Volume I, further work is suggested in a major "weak link" area of electric drives: the low coolant temperature requirements of the solid-state power electronic components. Raising these temperatures from their current maximum values of approximately 65°C would contribute to a large savings in cooling system complexity and volume.

9.2.5 Fuel consumption

The fuel tank occupies 39.3 cu. ft (23 percent of the propulsion system volume) for the dAIPS; 49.6 cu. ft (28.3 percent) for the tAIPS; and 77 cu. ft (26 percent) for the AGT 1500 turbine in the M1 tank. Clearly, for the battefield day, the AIPS engines are more fuel efficient than the AGT 1500. The corresponding engine volumes are 34 cu. ft (20 percent) for the dAIPS; 24.7 cu. ft (14.1 percent) for the tAIPS; and 30.7 cu. ft (10.5 percent) for the AGT 1500.

From these numbers, it can be concluded that fuel economy is important to total system compactness. Also, from a logistics and cost standpoint, fuel economy is important and must be considered.

9.2.6 Propulsion system fluids

While it is reasonable to assume future commercial fuels and lubricants will satisfy performance requirements of future commercial heavy-duty diesel engines, this same assumption **cannot** be made for future high-output/low-heat rejection military diesel engines. That is, it is safe to assume that future military fuels and lubricants requirements **will not** be incorporated into future commercial fuels and lubricants. The traditional/unique military engine requirements simply cannot be included in the commercial fuels and lubricants (F&L) specifications mainly because this inclusion would unjustly elevate the cost of commercial products while commercial engine suppliers would question the need.

The Army's future higher power density propulsion system development must be cognizant of the propulsion system fluids (i.e., fuels and lubricants) requirements. Further increase in operating temperature will place extreme stress on the system fluids. Projected engine cooling system volume reduction is estimated to be from 8 to 22 percent if bulk oil temperatures can be raised from 171 to 190°C (340 to 374°F). This increase in oil temperatures will present research opportunities for an on-board fuel preconditioning system, high-temperature lubricant development, and novel engine lubrication systems that are discussed further in Section IX.2.6.2, Appendix IX, Volume II. As stated in Section 9.2.4.1 of Volume I, a 20-percent reduction in transmission volume can be expected with development of a high-temperature lubricant that will permit use of a common sump for the engine and transmission.

The unique military F&L requirements and subsequent risks are shown on the following page.

MILITARY ENGINES ARE EXPOSED TO ENVIRONMENTAL EXTREMES THAT PLACE FUELS & LUBRICANTS AT RISK

- HIGH POWER-TO-WEIGHT AND POWER-TO-DISPLACEMENT RATIOS
- SEVERE DUTY CYCLE; LOW MILEAGE / YEAR
- AMBIENT TEMPERATURE EXTREMES (–60° TO 120°F) AND WIDE FLUCTUATIONS
- FREQUENT EXPOSURE TO DUST AND POOR WEATHER
- LIMITED ENGINE COMPARTMENT SPACE / COOLING AIRFLOW
- OFTEN OPERATE WITH DAMAGED OR DETERIORATED COOLING SYSTEMS
- RESULTANT HIGH THERMAL STRESS ACCELERATES FUEL/LUBRICANT DETERIORATION
- WORLDWIDE OPERATIONAL DEMANDS REQUIRE ACCEPTABLE PERFORMANCE ON HIGH-SULFUR / HIGH END POINT DIESEL FUELS AS WELL AS LOW-SULFUR / LOW-AROMATIC KEROSENE FUELS
- BROAD OPERATING ENVIRONMENT RAISES QUESTIONS ABOUT FUEL THERMAL STABILITY, FUEL SYSTEM DEPOSITION, FUEL LUBRICITY, AND INJECTION SYSTEM WEAR; AND ENGINE LUBRICANT TRIBOSYSTEM DURABILITY IN MILITARY DIESELS

9.3 Estimates of Possible Increases in Compactness

9.3.1 Introduction

While there will inevitably be a lack of preciseness, it will be helpful to have estimates of possible increases in compactness assuming the required research and development is done. Two different approaches were followed in obtaining estimates. The first approach was to ask the presenters to make estimates, while the second was for the BRC to make estimates. The reasoning behind the BRC's estimates follows.

This section includes the estimates resulting from both of these approaches. In considering the estimates made by the BRC, note that the component reductions discussed in Sections 9.3.3 through 9.3.8 are not necessarily additive. Also note that summary estimates for 750- and 1,000-bhp systems are presented in TABLES IX-13 and IX-14 of Appendix IX, Volume II.

9.3.2 By reduction in unused volume

Unused volume is a poorly defined term. For BRC estimations in Volume I, it is defined as the volume of a box that would enclose the system minus the dunked volume (displaced volume if submerged without leakage). Other estimators may use different definitions. For example, in TABLE 9-1 the above definition is used to obtain "TACOM Estimates – Existing Systems" and the BRC value of 10.0 cu. ft of unused volume. It is presumed but not known that the "Manufacturer/Contractor Projections" in TABLE 9-1 and the values in Volume II approximate the same definition.

Using the BRC definition, unused volume will never go to zero. However, in the dAIPS, it is estimated that a reduction of 5 to 7 cu. ft in unused volume could be achieved if a common engine-transmission fluid and sump could be used. In addition, some small packaging gains could probably be made, particularly if an electric drive is used.

9.3.3 By use of more nearly stoichiometric combustion

At full load, the dAIPS currently operates with an air/fuel ratio of 28 to 1. For estimation purposes let us assume that, after a decade of research, the difficulties listed in Section 8.2.3 are overcome such that a full load air/fuel ratio of 18 to 1 could be achieved at the same engine rpm, thermal efficiency, and unit power heat rejection rate. Under these assumptions, all the combustion air handling components (engine, 34 cu. ft; charge air cooler, 16.4 cu. ft; and air cleaner, 8.4 cu. ft, for a total of 58.8 cu. ft) could be reduced by about 40 percent, which would be a total reduction of 23.5 cu. ft. Not all the assumptions can be met, but it is estimated that reductions of 7 cu. ft for the engine, 3 cu. ft for the charge air cooler, and 1 cu. ft for the air cleaner can reasonably be expected.

9.3.4 By increasing displacement rate

Displacement rate can be increased two different ways. The first is to increase rpm and the second is to go from four- to two-cycle operation. Both approaches increase the thermal loading

on the engine cylinder. Increasing rpm generally increases friction, so the increase in power is not linear with increased rpm. The mean piston speed of the MTU 883 at 3,000 rpm is 2,756 ft/min, while the mean piston speed of the dAIPS at 2,600 rpm is 2,218 ft/min. Thus, a 25-percent increase in rpm seems reasonable. In theory, this increase could result in a 25-percent displacement decrease to maintain the same displacement rate. In view of the many nonlinearities, an engine volume decrease of 10 to 15 percent (5 cu. ft) seems achievable.

9.3.5 By increasing manifold pressure

For the same manifold air temperature, the mass of air is directly proportional to manifold pressure. If the same air-fuel ratio is maintained, BMEP increases directly with increased manifold absolute pressure. It follows that both thermal and mechanical loading go up with increased manifold pressure. The dAIPS maximum power BMEP of 263 psi is intermediate between the 311 psi for the CV12 and the 233 psi for the MTU 883 but considerably less than the 473 psi of the low-compression-ratio Hyperbar. A 10-percent maximum power BMEP increase seems achievable. This increase would give an estimated engine volume reduction of 2 cu. ft.

9.3.6 By improving steady-flow machinery

This machinery includes turbochargers, heat exchangers, and air cleaners. Little direct volume reduction is anticipated in this section. However, the efficiency of the cooling fans is an area for improvement. An increase in fan efficiency would, in effect, decrease the required size of the engine, steady-flow machinery, and fuel tank. A volume reduction of 2 cu. ft seems achievable.

9.3.7 By improving the mechanical transmission

The volume of mechanical transmissions could be reduced by better materials and higher temperature oils. It is estimated that a volume reduction of 20 percent (7 cu. ft) is achievable.

9.3.8 <u>By using electric drive</u>

Prediction of potential propulsion system volume reduction by use of electric drives awaits the results of the study previously recommended. See Section 8.2.5 for recommended electric drive study.

9.3.9 <u>Summary of estimates</u>

Propulsion system/component volume estimates are shown in TABLE 9-1. All data shown in TABLE 9-1 are <u>presenter</u> estimates (TACOM or Manufacturer/Contractor) except for the last two columns, which are BRC estimates achievable in the next decade. System and component volumes of existing systems, including the AGT1500 turbine as well as system volume estimates at the end of a decade, are shown in TABLE 9-1. It should be noted that the RPI estimate under "System Estimates" is for a 1250-hp engine, while the others are for 1500-hp engines.

The third from the last column was constructed using the lowest <u>presenter</u> volume estimates for any component using comparable technologies and, in that sense, represents the minimum estimated volume achievable in the next decade. The second from the last column presents BRC estimates of what could realistically be achieved in the next decade. The last column shows the BRC estimated achievable volume reductions in percentages, all versus dAIPS. While the assumptions made by the presenters were not specifically stated, the BRC estimates assumed an increased fuel/air ratio, higher displacement rate, higher manifold pressure, transmission technology improvements previously discussed, and a common engine/transmission oil sump.

No Manufacturer/Contractor presenter estimates for weight reduction were received. However, to provide a methodology for determining the impact on the overall vehicle volume and weight when applying advanced propulsion systems, TACOM was requested to conduct such analyses for both 30-ton and 60-ton vehicles. The results of these volume and weight analyses are illustrated in TABLES IX-12 through IX-19, Section IX.3.9, Appendix IX, Volume II. For the 30-ton vehicle, the dAIPS engine was scaled down as described in Section IX.3.9, Appendix IX,

Volume II. Estimated reductions in propulsion system and hull weight were made using the procedures outlined in Section IX.3.9, Appendix IX, Volume II.

TABLE 9-1. 60-ton, 1,500-bhp Propulsion System Volume Estimates (cu. ft)

	TACOM Estimates – Existing Systems							Manufacturer/Contractor Projections										
						AIPS				Adiabatics			DDC*				BRC	
Component	AGT 1500	MTU 883	Perk CV12	Poyad HyBar	RPI	Turb	Dsl	Cum	Cat	Rdcm	Stmet	Stad	Low	High	RPI 1,250 hp	LCTE	Vol	%†
Engine	30.7	34.4	34.0	35.0	34.0	24.7	34.0	--	19.0	10.0	25.0	25.0	15.0	27.0	19.0	19.0	22.0	35
Trans‡	40.0	35.0	35.0	35.0	35.0	29.3	34.9	55.3§	35.0	35.0	32.0	32.0	20.0‡	30.0	17.0‡	20.0	28.0	20
Cooling	15.0	33.0	41.0	40.0	30.0	5.8	16.4	--	20.0	17.0	10.4	6.0	12.0	16.0	6.0	6.0	13.0	21
Air filter	30.6	8.4	8.4	8.4	11.8	10.6	8.4	6.4	8.4	8.4	5.6	5.6	6.0	8.0	1.0	5.6	7.0	17
Exhaust	9.7	2.0	2.0	2.6	2.0	9.2	2.0	2.0	2.0	2.0	1.3	1.2	2.0	2.0	1.0	1.2	2.0	0
Fuel tanks	77.0	43.9	45.0	46.6	47.0	49.6	39.3	39.3	33.4	39.3	39.3	39.3	30.0	35.0	24.2	30.0	35.0	11
Batt/misc	18.0	18.0	18.0	18.0	18.0	21.5	18.0	18.0	18.0	18.0	15.0	12.0	18.0	18.0	15.0	12.0	16.0	11
Unused♦	70.0	40.3	40.6	40.3	34.2	24.3	17.0	17.0	20.0	17.0	17.0	17.0	17.0	17.0	5.0	17.0	10.0	41
System – Env. Vol.	291.0	215.0	224.0	225.9	212.0	175.0	170.0	138.0	155.8	146.7	145.6	138.1	120.0	153.3	88.2	110.8	133.0	22

* DDC = Detroit Diesel Corporation
BRC = Blue Ribbon Committee
HyBar = Hyperbar
RPI = Rotary Power International
Turb = Turbine
Dsl = Diesel
Cum = Cummins Engine Company, Inc.
Cat = Caterpillar
Rdcm = Randcam
Stmet = Stoichiometric
Stad = Stoichiometric and insulated (adiabatic) (stoichiabatic)
LCTE = Lowest Comparable Technology Estimate

† Percent improvement over dAIPS
‡ Transmission = The DDC volume of 20.0 and the RPI of 17.0 assume electric drive.
§ Includes engine, transmission, and cooling
♦ See Section 9.3.2 in Volume I for the definition of unused volume.

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